ACOUSTIC PROPERTIES OF MACROPHYTES: COMPARISON OF SINGLE-BEAM AND MULTIBEAM IMAGING WITH MODELING RESULTS

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1 INTRODUCTION

Acoustic methods for habitat mapping are recognized as a very efficient tool for the assessment of benthic communities and as an important source of data for marine environment modeling and management [1, 2]. This is especially true in periglacial ecosystems, where the intense and dynamic processes due to global warming need efficient and fast methods for tracking of the key environmental factors [3], in order to understand how the distribution and composition of marine plants and animals and the marine carbon cycle is affected by climatic changes in Arctic. One of these key features is macrophytobenthos spatial distribution which is related to primary production estimations.

Macroalgae are quite large, underwater plants, living attached to the bedrock or boulders and stones. They play a significant role as a habitat for benthic communities and, as primary producers and are one of the basic components of the very sensitive Arctic food chain. In Kongsfjord, macroalgae grow in the littoral and sub-littoral zones, mainly 0-30 m deep [4], in small, patchy communities or densely over hard substrata. Most of the Arctic seaweed species are represented also around the UK, which allowed collecting samples and carried out some experiments in the university of Bath laboratories.

Even though single-beam and multibeam echosounder signal analyses have been used for many years for seaweeds and seagrass mapping [2, 6, 7, 8], the potential for this purpose has not been fully explored yet and is a fast growing area of interest for acousticians. These researches have shown significant influence of algae layers on normal-incidence backscattering, but there are still many doubts about how macroalgae affect scattering over a wide range of angles, and if they are always clearly distinguishable from the substrata [9].

The main purpose of this research was to determine the best tools, or combination of acoustic tools, to quantify the area and biomass of macrophytes in a Svalbard's fjord, Kongsfjord. One important part of this task was to describe macroalgae acoustic properties and estimate the reflection and absorption coefficients of the seaweed layer considering their angular response. The second part was to prepare methodology and signal analysis techniques for single beam and multibeam echosounders data collection and processing, so that macroalgae communities can be recognized and their areas estimated [8]. There are only a few works focused on seaweeds acoustic properties so far [10], which is why the experimental measurements are so important. This paper focuses on the first task, presenting some experimental data of sound speed values in algal blades and their reflection coefficients for different acoustic signals and incidence angles.

2 ACOUSTIC IMAGING OF MACROPHYTES

2.1 Study area and Arctic macroalgae

The acoustic data were collected in Arctic Summer 2007. The place of investigation was Kongsfjord, in North-West Spitsbergen (Fig.1). It is an open fjord, exposed to the Atlantic and a warm water inflow from the West Spitsbergen Current, which can change the local environment very distinctly. The fjord covers 230 km², is 26-km long and 4-11 km wide [5]. There is a large, international polar station which hosted our research team.

Biological studies conducted for many years in Kongsfjord show that the densest kelp forests grow in the sub-littoral zone, between 5 – 15 m depth and with dominant species like *Alaria esculenta*, S*accharina latissima* and *Laminaria digitata*. These are large plants with heights up to 2 – 3 m. The euphotic zone for macroalgae reaches 30 m down but most of the biomass appears down to 15 m [4,5]. It means that our area of interest along the coastal zone was as large as 18.5 km². Data collection was carried out from a small, aluminium boat. The SBES transducer was pole-mounted on the starboard side and the MBES transducer was pole-mounted in parallel on the port side, both devices linked to their own GPS receivers. All acoustic transects were planned every 25 – 100 m, perpendicular to the shore line, although there were some deviations due to underwater rocks close to the water line and drifting icebergs. Overall, during the 2 weeks of measurements, acoustic data were collected over a total area of 3.8 km² (Fig.1).

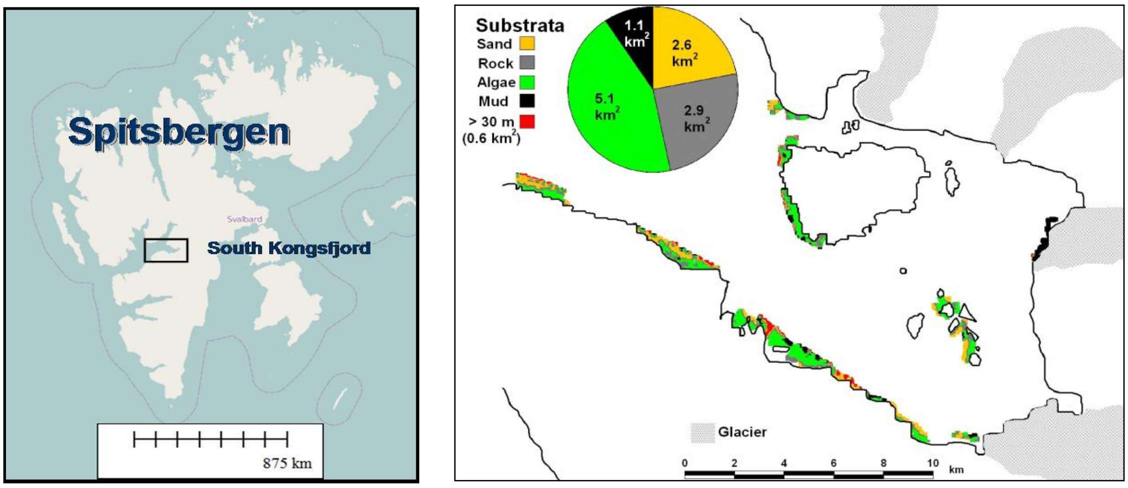

Fig.1: Kongsfjord, south part on the left image and inner part area (right image) with benthic substrata information from SBES classification data, collected during this expedition [11].

2.2 Single beam echosounder research

During the field work, the single beam echosounder Biosonics DTX was used. It operates at 420 kHz with a narrow 3-dB beamwidth of 5.2°. Main settings used for data collection were as follows: 30 m range, with a pulse length of 0.1 ms. It performs with a resolution of ~0.3 – 0.9 m (according to depth) × 0.02 m and the signal is recorded over 57 samples per meter. Obtained SV values (i.e. mean volume backscattering strengths) were preprocessed by the built-in system, including for signal loss compensation.

Received echo envelopes for each ping were analyzed and compared with biological data, to estimate how macroalgae's presence on the seabed influences the acoustic signal. There were only 4 places suitable for biological sampling, where divers collected seaweeds from a 0.25-m^2 area limited by frames. Biologists then calculated the biomass and taxonomic content of seaweeds for each sample. Figure 2 (left) presents an example of an echogram from the area of the first dive. White vertical lines mark a part with 5 pings, which comes from a sampling station before the dive. The footprint of this part of the echogram is 0.24 m^2, similar to the sampling frame area. Figure 2 (right) shows the central ping's backscattering strength as SV and TS values (i.e. mean target strength) related to sample depths.

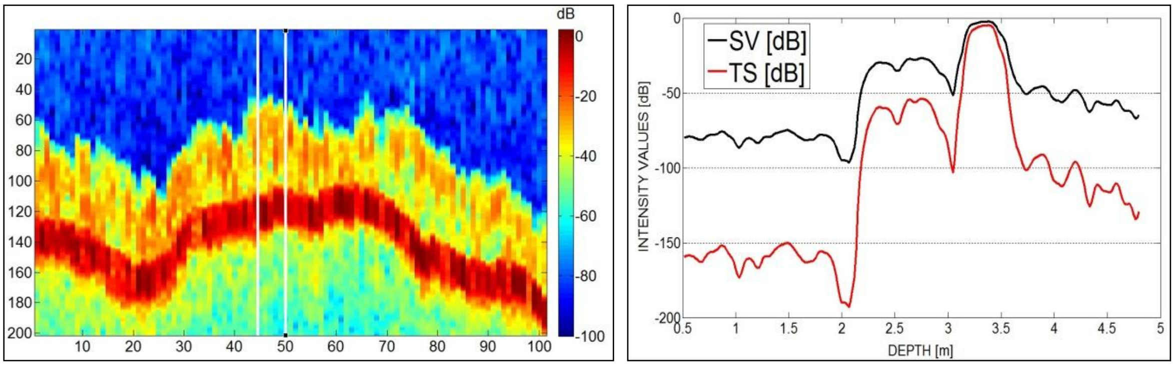

Fig.2: SBES echogram (left image) with two line markers delineating a ground-truth area at point 1. The diagram on the right shows an echo envelope of a central ping from this area, as SV and TS values variations in depth.

Backscattering strengths (Fig.2, right) present a maximum value of seabed reflection at a depth of 3.3 m. The seaweed echo appears between 2.1 m 3 m depth with mean SV = 28.6 dB and mean TS = 52 dB. It is easy to notice that macroalgae height estimation based on SBES data is 0.9 m, in good agreement with divers' description of kelp layer height in this place, estimated as 1 m. Table 1 presents a comparison of biological information and acoustical data from all 4 diving points.

Table.1. Comparison of data derived from biological samples and SBES data.

	Point 1	Point 2	Point 3	Point 4
Sampling area [m^2]	0.25	0.25	0.25	0.25
Biomass [kg/0.25 m^2]	1.19	2.21	2.38	2.38
Mean SV [dB]	-28.6	-34.8	-33.8	-32.2
Mean TS [dB]	-52	-54	-48	-41
Mean Height, samples [m]	1	0.3-0.5	0.3-0.5	0.3-0.5
Mean Height, SBES [m]	0.9	0.45	0.38	0.49

These results (Table1) show that SV values are not correlated with the biomass of macroalgae, implying there are other important factors influencing backscattering signals. Nevertheless, these SV values differ significantly from bottom reflections and noise levels in water column, making them acoustically visible on the SBES echogram.

2.3 Multibeam echosounder research

The Imagenex 837 Delta-T multibeam (MBES) creates up to 420 beams per swath (120°) during beamforming, at a frequency of 260 kHz. Data were collected using 120 beams, yielding for each beam a width of 1° across-track and 20° along-track. Intensities were acquired for the entire water column as non-dimensional values coded on 8 bits. Full-range water-column data was collected, and not only single intensities from the seabed as usually done. The nominal vertical resolution of the MBES is 0.2% of the range selected by the user (i.e. 2 cm at 8 m). The digital signal is presented as 500 samples per range for each beam. Data were acquired for three times the depth range, usually 10, 20, 30 and 40m.

An example of MBES swath (Fig. 3) comes from an area of biological sampling (site 1). There was a dense and high macroalgae community in a few meters' radius. At this depth, 3.9 m, the multibeam footprint is 18.6 m^2, 740 times greater than that of the Biosonics DTX, showing the huge potential of fast habitat mapping using MBES. Mean signals intensity charts at all angles and for two habitats are presented on Fig.3 (right). The black line represents mean values recorded over a dense kelp forest. Higher values can be observed only in the center of ping, for beams between -16.5° +16.5°. Unfortunately, outer beams values do not differ much from the red line, which comes from a bare seabed.

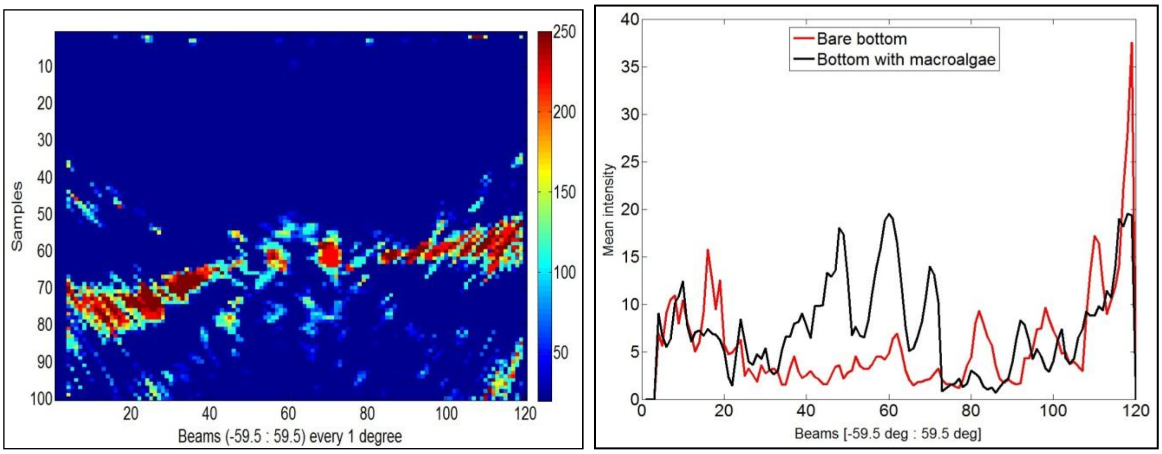

Fig.3. MBES intensity image from a swath (slant range corrected) at the sampling point 1 (left), echogram resolution is 0.08m/sample, mean depth between beams 60:90 is 3.9m. The right diagram presents mean intensity values of samples from above the bottom line, depending on beam angle: red line for the bare seabed and the black one for macroalgae layer.

2.4 Results of acoustic investigations of macrophytes

Examples of SBES and MBES data, compared with biological results show that for normal-incidence scattering there is a significant reverberation level for macroalgae layer, but that there is no correlation between registered SV and kelp biomass. It means that not only volume and density of seaweeds play a role in acoustic backscattering and signal absorption but also some surface scattering phenomena. It is possible that, for such high frequencies, this second part is even more important.

Comparing SBES echoes with MBES data, there are no signs of macroalgae in the outer beams in areas where they are known to grow densely. Figure 3 (right) shows mean intensity values from area above the bottom line, from two swaths, first from an area covered by seaweeds (Fig.4, right, black curve) and second (Fig.4, right, red curve) from the bare seabed at the same depth (4 m). One can see important differences between those intensities, only in the central beams, i.e. angles from -16.5° to +16.5°. Macroalgae coverage was around 100% in the insonified area but their influence on backscattering intensity is noticeable only in the MBES central beams. This phenomenon could be either a problem of frequency or equipment quality, or the acoustic properties of macroalgae when imaged at more oblique angles.

3 ACOUSTIC MODELING OF MACROPHYTE SCATTERING PROPERTIES

Literature shows only a few main papers describing macroalgae in an underwater acoustics context. Carbo and Molero [10] investigated *Gelidium* seaweed acoustic detection based on a tank experiment, although this type of seaweed is very different to species dominant in the Arctic. This was a very important source of information about normal-incidence reflection from algae. The acoustic impedance ratio $Z_{g(rass)}/Z_{w(ater)}$ for the water-plant boundary was measured as 1.029 and 1.1, for 200kHz and 500kHz respectively, with respective absorption coefficients of 1.22 and 3.23

dB/m. These small values make *Gelidum* almost invisible to acoustic waves when compared to the sandy bottom background, but this situation changes significantly when the density and height of the macroalgae layer increase. Macroalgae from Kongsfjord are larger and denser than *Gelidum*, which leads us to assume that their interaction with sound waves would be more easily detectable.

A theoretical approach for estimating scattering of sound by algae was presented in Shenderov [12], but he pointed that density and sound velocity in kelp blades were unlikely to ever been measured, and used the same shape parameters also very important for scattering models. To address this, some of these features were measured in tank experiments.

3.1 Experiment methodology

Fresh macroalgae, mostly *Laminaria digitata, Saccharina latissima* and *Fucus* species, were collected in Lynmouth and Combe Martin harbours, during low tide, on the South-West part of the English shore. They were kept in slightly salted water for a night. After this time, no serious damage or decomposition were noticed. The following experiments took place: a) sound speed estimation in algal blades using direct sound speed profiling in a tank; b) sound speed measurements with two transducers; c) density of plants measurements.

A digital time-of-flight velocity sensor (Valeport Midas SVX2) was used for the first type of sound speed measurements, it transmits a high-frequency (2.5-MHz), short pulse, which reflects from a steel plate and is received by a monostatic transducer (Fig.4, left). The accuracy of this equipment is 0.03 m/s and the range of measurements is 1400:1600 m/s. It was also equipped with pressure and temperature sensors.

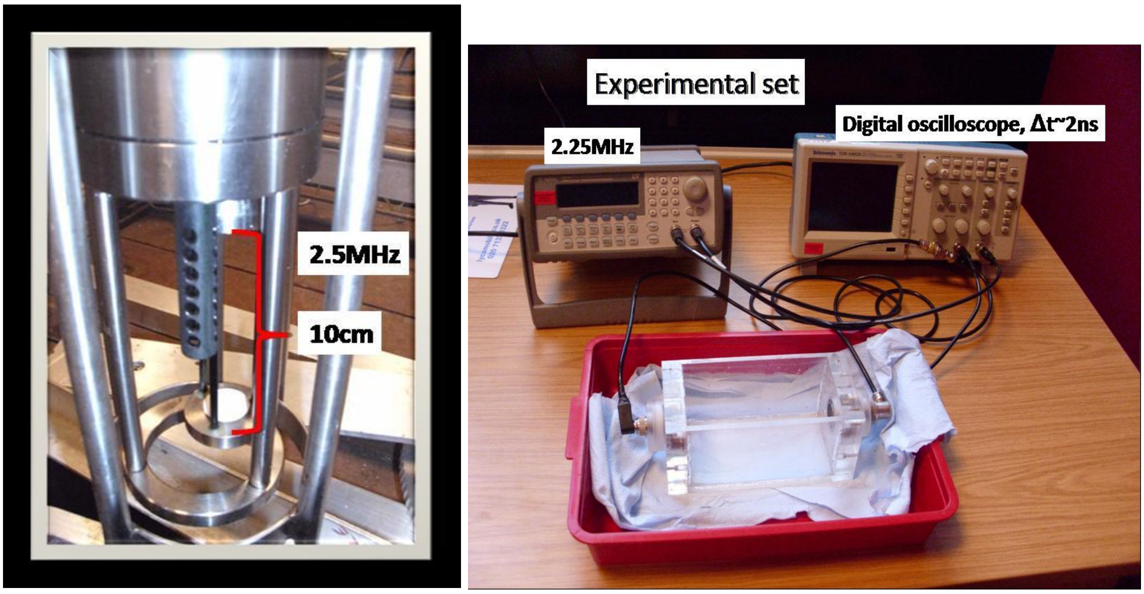

Fig.4. Two devices for sound speed measurements: Valeport Midas SVX2 (left) and a desktop set for time-delay measurements of sound waves between different media (right).

The sound speed V_w measured wth the Valeport sensor in clear water and the mean sound speed V_m with part of a macroalgae blade under the transducer, were used to calculate the sound velocity inside a plant layer of known thickness D_q:.

$$V_g = \frac{D_g}{\frac{D_p}{V_m} - \frac{D_p - D_g}{V_w}} \tag{1}$$

Where D_p is the distance between transducer and plate and V_g is the sound speed inside a part of blade.

The crucial measurement of the blade thickness D_g was difficult, especially because it varies a lot in some of the species, like *Saccharina latissima* (Fig.5), with a very undulated and uneven body. This was measured with a digital micrometer.

The ultrasonic apparatus was made from two transducers mounted on walls of a small, 15-cm long, container filled with water. One of the transducers transmitted a pulse with a frequency of 2.25 MHz and the other one is connected to the oscilloscope which displays the received signal (Fig.4, right). Comparing travel time of sound wave for water without any obstacles and after putting a seaweed blade in the water path between transducers, we obtained a time delay *Δt*, yielding estimates of *Vg* for the macroalgae collected. Kelp blade thickness was also a crucial factor here, as:

$$V_g = \frac{D_g}{\frac{D_g}{V_w} - \Delta t} \tag{2}$$

The density of each plant was deduced from their volume and weight (Table 2).

3.2 Experimental results and modeling of macroalgae scattering properties

Blade samples were cut out from the *Laminarias*, *Saccharina latissima* and *Fucus* samples and placed in the Valeport SVP and ultrasonic apparatus (Fig. 5). These measurements were done in fresh water, with a sound speed of 1,466 m/s in the tank, and 1,480 m/s in the container, because water warmed up very fast in such a small vessel. These sound speeds are similar to those in the Arctic, as recorded using a CTD profiler during our 2007 expedition to Kongsfjord, where mean sound speed up to 30m depth was 1,468 m/s.

Fig.5. The most common macroalgae samples tested in the laboratory: *Saccharina latissima* (left image) and different types of *Laminaria* (right picture).

Table 2. Densities and sound speed values for different types of macroalgae

	Density [kg/m^3]	**Vg from Valeport [m/s]**	**Vg from ultrasonic set [m/s]**
Laminaria sp.	1102	1579	1591
Saccharina latissima	1137	1548	1555
Fucus without pneumacotysts	1010	1568	1557
Laminaria stipe	1247	1602	1628

Results of sound speed in underwater plants samples obtained from both type of devices show large agreement (Table 2). All species without pneumatocysts (bladders with gas) are denser than sea water and the sound speeds in their blades and stipe are bigger than that of sea water. It means that the impedance ratio between water and seaweeds is not equal to 1. The mean acoustic impedance ratio for sea water in the Arctic and the seaweeds would in fact be Z_g/Z_w=1.16.

Other very important factors for scattering models are the mean size of kelp blades and the roughness of their surface. *Laminarias*, without bladders, are very flat, with RMS heights of the leaf surface less than 0.2 mm and leaf thickness around 0.9 mm, without too much variation. According to the Rayleigh parameter, they can be treated like smooth surfaces [13]; sound reflection would mostly be in the specular direction. However, even flat macroalgae, when placed over several layers, can create significant roughness and influence the overall oblique incidence scattering.

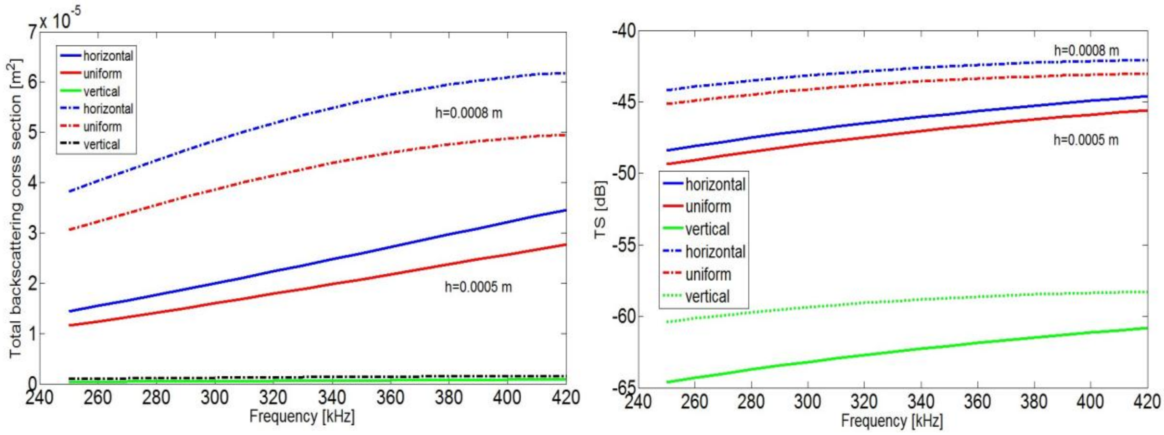

Fig.6. Estimations of total backscattering cross-section and target strength (TS) for macroalgae leaves layer, insonified by an echosounder beam with the parameters from the Biosonics DTX. Leaves are undulated with 5-cm cycles (like Saccharina latissima) and a RMS height of 6 mm. Leaf area is 0.035 m^2. There are two different leaf thicknesses: h=0. 5 mm and h=0.8 mm. Both parameters are calculated for three kinds of leaf inclinations: horizontal, uniform and vertical.

When investigating macroalgae at high frequencies (>100 kHz) it is more realistic to assume that their surface is very rough compared to the wavelength and consider the incoherent reflection component. The work for modeling backscattering from rough surface of macroalgae layer, including absorption coefficient, is in progress, shown here is the estimation of the total backscattering cross-section for normal incidence signal and for different frequencies (Fig. 6, right), for rough seaweed surface. A very important parameter is the leaf thickness *h*. For thicker macroalgae, there is more reflection loss and contrast between bottom and macroalgae layer scattering is stronger.

4 DISCUSSION

These results are the first step toward a more complex modeling of macroalgae scattering. These analyses pay attention to all crucial parameters of macroalgae morphology. According to our knowledge, this is the first time that some of them, like density and sound velocity in kelp blades were estimated with such accuracy. There are still many questions to answer, in particular the angular dependence of backscattering on macroalgae compared to the underlying bottom. Scattering depends not only on the surface roughness and impedance of leaves but also on the imaging frequency and on leaf thickness. The next step would be to calculate backscattering cross-section for several layers of macroalgae, such as observed in the field, and relate acoustic values to estimates of their abundance.

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